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An experimental and numerical investigation on micro rolling for ultra-thin strip

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Abstract

The demand for miniaturized parts and miniaturized semi-finished products is increasing nowadays, because microforming processes can improve production rate and minimize material waste due to less forming passes. However, traditional macro metal forming processes and modelling cannot be simply scaled down to produce miniaturized micro parts. In this study, a 2-Hi micro rolling mill has been successfully built. Experimental and numerical investigations on the micro rolling process for ultra-thin SUS 304 stainless steel strip have been conducted. The experimental results show that the micro rolling deformation of ultra-thin strip is influenced by size effect which results from the specimen size difference and this size effect is embodied in the flow stress and the friction coefficient. Analytical and finite element (FE) models in describing size effect related phenomena, such as flow stress, friction, rolling force and deformation behaviour, are proposed. The material surface constraint and the material deformation mode are critical in determination of material flow stress curve. The analysis of surface roughness evolution with rolling conditions has also been performed. The identified analysis on deformation mechanics provides a basis for further exploration of the material behaviour in plastic deformation of micro scale and the development of micro scale products via micro rolling.

Keywords

ultra, thin, rolling, micro, investigation, numerical, experimental, strip

Disciplines

Engineering | Science and Technology Studies

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An experimental and numerical investigation on micro rolling for ultra-thin strip

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Abstract The demand for miniaturized parts and miniaturized semi-finished products is increasing nowadays, because microforming processes can improve production rate and minimize material waste due to less forming passes. However, traditional macro metal forming processes and modelling cannot be simply scaled down to produce miniaturized micro parts.

In this study, a 2-Hi micro rolling mill has been successfully built. Experimental and numerical investigations on the micro rolling process for ultra-thin SUS 304 stainless steel strip have been conducted. The experimental results show that the micro rolling deformation of ultra-thin strip is influenced by size effect which results from the specimen size difference and this size effect is embodied in the flow stress and the friction coefficient. Analytical and finite element (FE) models in describing size effect related phenomena, such as flow stress, friction, rolling force and deformation behaviour, are proposed. The material surface constraint and the material deformation mode are critical in determination of material flow stress curve. The analysis of surface roughness evolution with rolling conditions has also been performed. The identified analysis on deformation mechanics provides a basis for further exploration of the material behaviour in plastic deformation of micro scale and the development of micro scale products via micro rolling.

Keywords Micro rolling, rolling characterization, surface roughness, size effect, ultra-thin strip.

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INTRODUCTION

Micro forming technology, a promising process for improving production rate and minimizing material waste, is now becoming more and more important in industries of miniaturized products. However the deformed material cannot be considered as a homogeneous continuum like the material in the macro scale metal forming because its behaviour in micro forming is characterized by only a few grains in the deformation area [1-3]. Therefore material deformation behaviour, such as friction characterizations and surface interactions, in micro scale should be well identified. A number of researchers have conducted related research work in micro forming. The influences of specimen thickness and grain size on material behavior have been investigated in the processing of thin metal sheets [2-4]. The analytical model combined with the share of surface grains can be developed to theoretically describe the decrease in flow stress with the findings from the material data obtained in the tensile test [5]. The evolution of friction behaviour from micro size to macro size is studied and a new uniform friction model is proposed based on the assumption of open-closed lubricant pockets [6]. The FE-based model has also been experimentally validated in terms of loads and enabled more accurate and flexible friction modelling [7]. Simulation has been applied in surface roughness modelling and size effect [8, 9]. Using the multi-region model, the coining process with micro feature is simulated to investigate the size effect [9]. Tribological analysis is of considerable importance in cold rolling process. The friction modelling and surface roughness deformation have been reported in refs [10-17]. Le and Sutcliffe apply a tribological model for mixed lubrication in rolling of thin strip and foil and this model indicates that the friction coefficient on the asperity contact is related to a theoretical oil film thickness and secondary-scale roll surface roughness [10, 11]. The surface is found to crush roughly with a large increase in contact area with bulk strain [15]. Friction coefficient clearly increases with an increase of the relative roughness and the ratio of tool roughness to specimen roughness [16]. The combined effects of friction, macroscopic deformation, roll roughness and lubricant viscosity influence the loads during cold rolling. For foil rolling, refs [18-22] have reported some related research. The deformation of foil rolling, where there are two stage reductions in the rolling deformation zone, is different and complex from the traditional macro metal forming. Fleck and Johnson [20, 21] assume that the roll profile includes a central flattened region for the deformed rolls, and the pressure is taken to be near Hertzian and the deviation of the roll profile from flat is incorporated by using a modified Winkler mattress model. However there are few researches focused on such hard material as stainless steel foil rolling in 2-Hi micro rolling mill.

In this study, experimental and numerical investigations have been conducted on ultra-thin strips of SUS 304 stainless steel by micro rolling to study and to evaluate the influence of the specimen size. The size effects on the flow stress curves and friction coefficient due to the variations of specimen size are clearly demonstrated. The analytical and FE models for describing the size effect related phenomena, such as the change of flow stress, friction and deformation behaviour are proposed. The experimental results can be used to validate the numerical model. A combination of the friction law and stress flow model, respectively can be brought together to be finally applied to micro rolling process.

EXPERIMENT AND SIMULATION

Experimental equipment and tested materials

The experiment consists of tensile test, friction test and micro rolling process. The tensile test and friction test provide the Stress-Strain curve and friction coefficient respectively, for the rolling process simulation. The research on rolling deformation behaviour for SUS 304 stainless steel is carried out on a micro rolling mill in dry friction without lubricating oil. The reduction in foil thickness for each pass varies according to the rolling schedule. The rolled foil is collected, measured and compared after each pass.

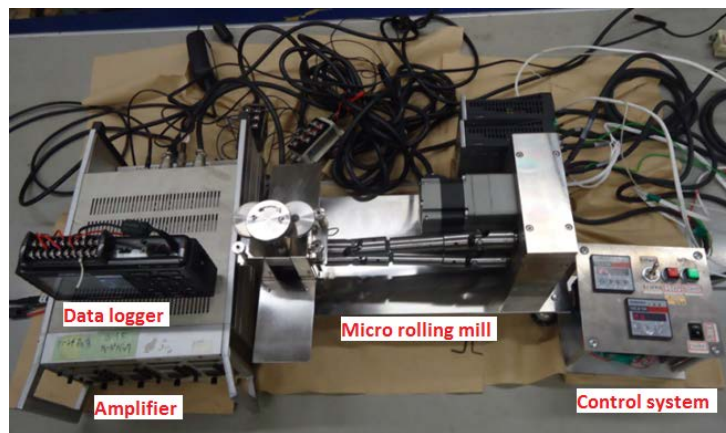


Fig. 1 New desktop micro rolling mill

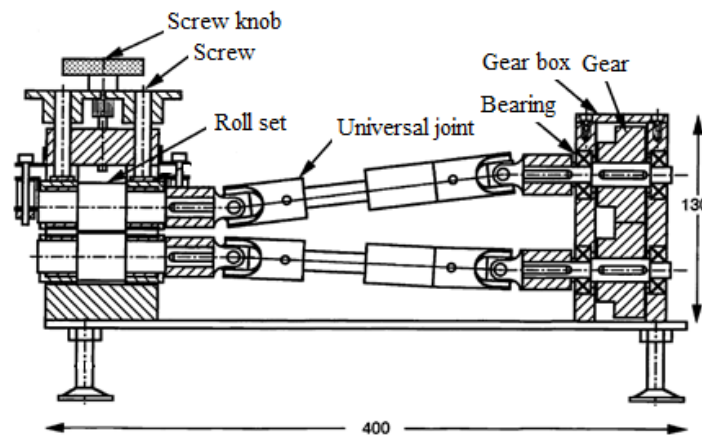


Fig. 2 Schematic rolling mill, unit: mm

Fig. 1 shows the new desktop micro rolling mill system, which includes micro rolling mill, control system, and data collection devices: pressure amplifier and data logger. Multi-pass and reversing rolling is available in this rolling mill. This new micro rolling mill is scaled down and easy to move and install on the desk and it is suitable for hard material rolling with low roll elastic deformation due to high rolling mill stiffness. The rolls are driven by motor via the gear system. The schematic rolling mill set is shown in Fig. 2 where the size of micro rolling mill is indicated. The length and height of rolling mill set are only 400 mm and 130 mm, respectively.

Various thickness reductions can be obtained through adjusting roll gap by the screw knob in Fig. 2.

Table 1 Rolling mill description

Rolling mill	Work roll (*diameter Φ 27 mm)		Roll barrel length	Rolling speed
	Material	Young's Modulus (GPa)		
2-Hi	SKD 11	210	29.5 mm	0-30 rpm
reverse mill	Cemented carbide	580		(0-42.4 mm/s)

The rolling mill is described in Table 1. It is noted that two materials of tool steel (SKD 11) and sintered hard alloy (cemented carbide) with high Young's modulus of 580 GPa are used as work roll materials in this rolling mill. The annealed austenitic SUS 304 stainless steel is prepared as experimental material and the 2-Hi desktop-scale reverse mill is used for multi-pass rolling. The initial material thicknesses are 100 μ m and 50 μ m with width of 15 mm, respectively. The chemical composition of SUS304 stainless steel is listed in Table 2.

Table 2 Chemical composition of SUS 304 stainless steel (wt %).

C	Si	Mn	P	S	Ni	Cr
0.05	0.44	1.18	0.033	0.001	8.22	18.23

Finite element modelling

The rolling simulation is carried out with the explicit dynamic finite element code, LS-DYNA. The SOLID164 element type has been used (a three dimensional 8 NODE solid element) for the simulation. Refined meshing is employed around the surface roughness of the rolled strip to improve the simulation accuracy and further surface roughness calculation [8].

Table 3 Properties of the roll and the rolled strip in simulation

Items	Roll	Steel strip
Material model	Elastic	Elasto-plastic
Density, kg/m ³	7.85x10 ³	7.85x10 ³
Young's Modulus, MPa	2.1x10 ⁵ (SKD 11)/5.8 x10 ⁵ (Cemented carbide)	2.1x10 ⁵
Poisson's ratio	0.3	0.3
Dimension	Roll neck in diameter: 9 mm Roll barrel in diameter: 27 mm	Thickness: 100 and 50 μ m Width: 15 mm

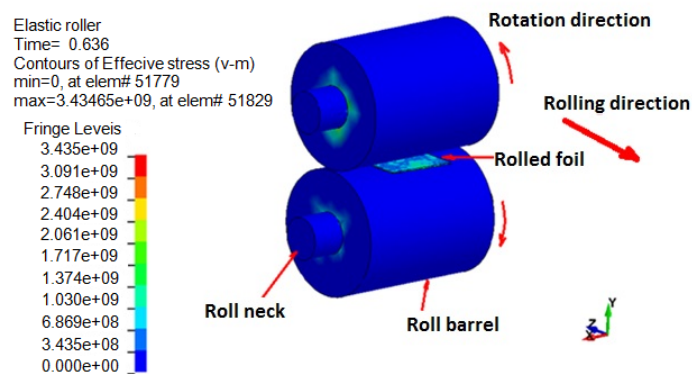


Fig. 3 Effective stress distribution

Table 3 lists the property parameters of the roll and rolled material used in the simulation which are similar to the parameters in the real rolling experiment. In the process simulation, the roll rotates with a fixed angular speed. There is a predefined initial speed of the strip and once in the rolling bite zone, the strip is pulled forward due to the friction of the rolls. A surface-to-surface contact condition is applied between the rotating roll and the thin strip. The rolled strip is assumed to be isotropic elasto-plastic. Considering the elastic deformation, the work roll is assumed to be linear-elastic material and roll neck to be rigid material. The roll rotation is driven by roll neck. Fig. 3 shows the effective stress distribution in the simulation model for 2-Hi rolling process. Y direction is normal direction and -Z direction is the rolling direction. The simulation result is evaluated on the basis of rolling force distribution and surface characterization of the rolled strip.

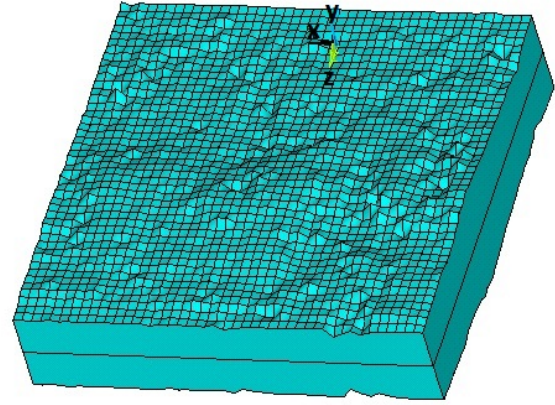
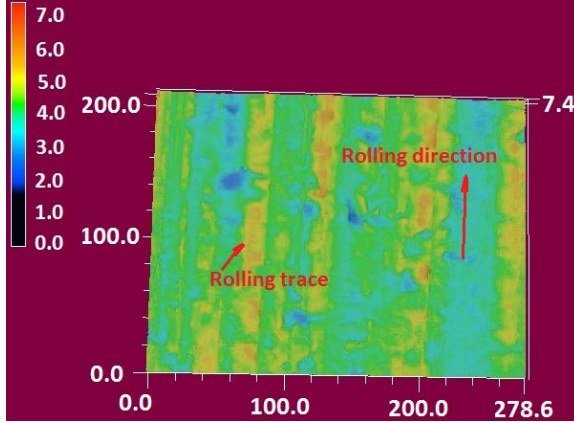


Fig. 4 Three dimensional measured heights of surface roughness, unit: μm **Fig. 5** Modelling surface roughness

Fig. 4 shows the three dimensional measured heights of surface roughness of the steel strip obtained from measurement system: 3D Laser Scanning Microscope, VK-X100 where the rolling direction and rolling trace have also been indicated. The surface roughness profile seems to be random but the characterization of height distribution is significant along rolling direction. In order to simulate the rolling process accurately, appropriate model for surface roughness across a large range of size scales is necessary. In this study the surface roughness has been modeled by ANSYS Parametric Design Language (APDL) based on the real measured value. Fig. 5 is the surface roughness modelling. Key points are firstly created at the base of the block and then bottom-up solid modelling approach is applied to create the block volume.

RESULTS AND ANALYSIS

Flow stress of thin foil

Scaled foil tensile test on standard commercial tensile testing machine is conducted for SUS304 stainless steel in different thicknesses. Fig. 6 shows the specimen size in tensile test. The nominal (engineering) stress-strain curves for different thicknesses of 50 μm and 100 μm along the rolling direction (0° to rolling direction) are shown in Fig7. It can be seen that the yield strength in the thickness of 100 μm is 5% higher than that in the thickness of 50 μm in the as-received materials. The results indicate that flow stress of SUS304 stainless foil decreases with the decreasing foil thickness in tensile tests.

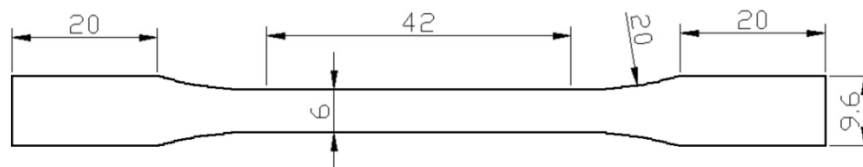


Fig. 6 Specimen in tensile test, unit: mm

The experimental result that the stress decreases with scaling down can be explained by surface layer theory. The deformation behaviour of the surface material is different from the inside one as the free surface material is less constraint yielding a decreased flow stress [2, 9]. The reduction of the flow stress with the thickness could have been resulted from the change of the volume ratio between the surface grains and the internal grains. This sort of ratio is smaller in marco-scale specimen where the surface material grains do not affect material

properties significantly. However, the volume fraction of surface grain is increased tremendously when the specimen size is scaled down to micro-scale. With a reduction of the absolute strip thickness, the surface zone becomes relatively more important, leading to a larger decrease in stress than the prediction based on geometric similarity. Therefore the material deformation behaviour will be influenced by the feature size of the specimen thickness in micro forming.

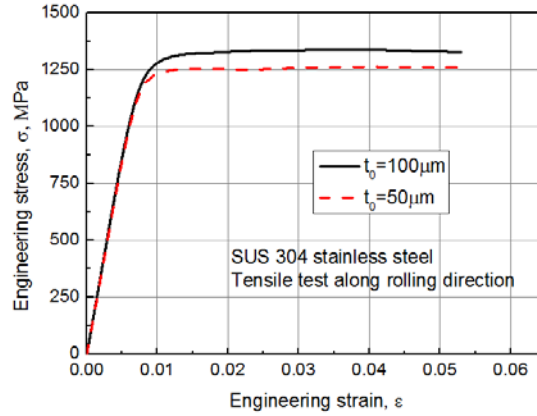


Fig. 7 Engineering Stress-Strain diagram for stainless steel

Size effect on friction coefficient

With increasing normal pressure, the real contact area increases due to more surface asperities flattened and the average friction coefficient increases as well. However, friction coefficient could decrease with an increase of close lubrication pool due to scaling down[6]. In order to investigate the size effect on friction coefficient and provide friction coefficient for simulation, the friction tester, as a simulator for micro forming, has been set up to measure the friction coefficient in dry sliding. The friction test is conducted through mounting new compression rig on standard commercial tensile testing machine [23]. In order to simulate the friction behaviour under the bulk plastic deformation of the strip, the contact pressure is varied and both surface and bulk deformations occur during sliding. The applied normal pressure is based on the contact pressure in rolling experiment.

The mean friction coefficient μ_{mean} can be calculated by Eq. 1.

$$\mu_{mean} = \frac{1}{L} \int_0^L \mu \cdot dl. \quad (1)$$

where, L is a sliding length and μ the friction coefficient for measured points during sliding in frictional test.

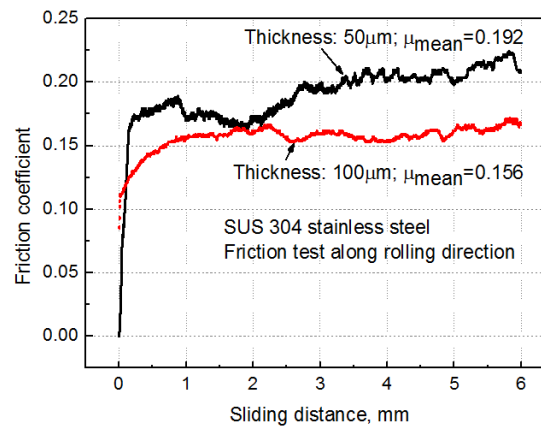


Fig. 8 Friction coefficient variation with sliding distance for different thicknesses

The results are shown in Fig. 8, demonstrating the relationship between the measured friction coefficients with sliding distances for different thickness specimens. It can be seen that the friction coefficient increases with

decreasing foil thickness. The average friction coefficients are 0.192 and 0.156 for the thicknesses of 50 μm and 100 μm , respectively, which will be applied in the simulation. A more interesting observation is that the friction coefficient increases with the sliding process and maximum values are 0.225 and 0.175 respectively for thickness of 100 μm and 50 μm . This is due to the produced heat and the changed contact statue during dry sliding.

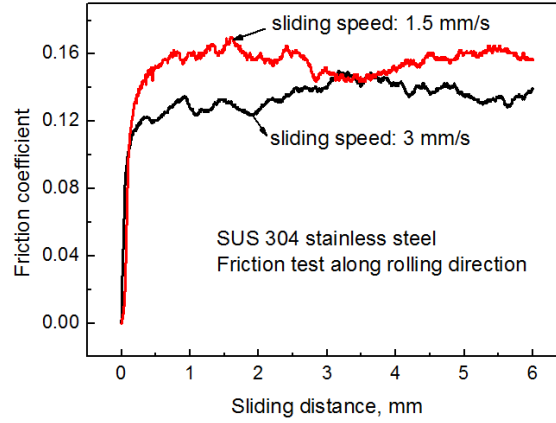


Fig. 9 Friction coefficient variations under two different sliding speeds, foil thickness: 100 μm

With similar experimental conditions except sliding speed, Fig.9 shows the average friction coefficient variations with different sliding speeds for the thickness of 100 μm . It can be seen that the average friction coefficient decreases with an increase of sliding speed. When the sliding speeds are 1.5 mm/min and 3 mm/min respectively, the average friction coefficients are 0.153 and 0.138 respectively. When the sliding speed is higher, the metal surface will soften due to the heat produced by the friction between the tool and the specimen. This softened layer acts as solid lubricant, which will cause friction coefficient to decrease with the sliding speed. Therefore the effect of speed on friction coefficient needs to be taken into account in the simulation. The friction coefficients under different speeds can be obtained from the friction test and its value can be applied in simulation through the linear interpolation based on the rolling speed accordingly.

Rolling experiment and simulation

A subroutine program in ANSYS has been set up. The detailed information of coordinates of nodes, faces, elements, and interface surfaces have been collected to evaluate the surface characterization in simulation.

The evaluated surface roughness R_a can be expressed by:

$$R_a = (1/a) \int_0^a |Y(x)| dx \quad (2)$$

where, a is evaluation length value and Y_x is the profile height function.

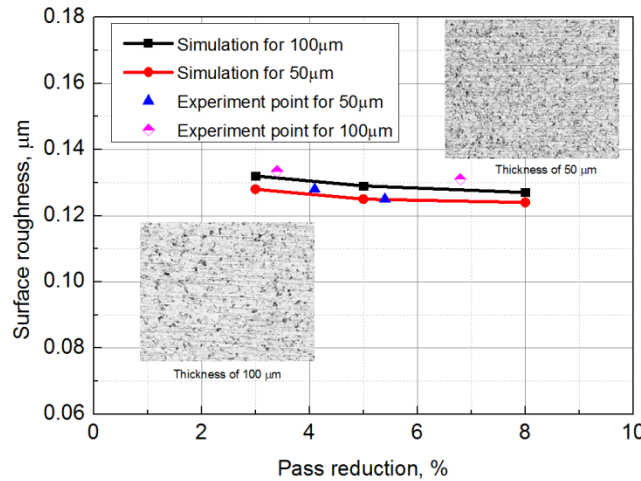


Fig. 10 Measured and predicted surface roughness

Firstly, the bulk volume can be obtained through bottom up modelling by APDL Language as shown in Fig. 5. After rolling simulation, the coordinates of nodes on the topmost surface are collected to calculate the surface roughness based on Eq. 2.

The surface roughness in experiment versus simulation is shown in Fig10. The initial surface roughnesses are 0.136 and 0.132 for 100 μm foil and 50 μm foils, respectively. It can be seen that the surface roughness decreases with an increase of pass reduction due to the reprinting or interaction between the rolls and the rolled strip. The simulation results are in agreement with the experimental values, and this has testified the validation of rolling simulation modelling.

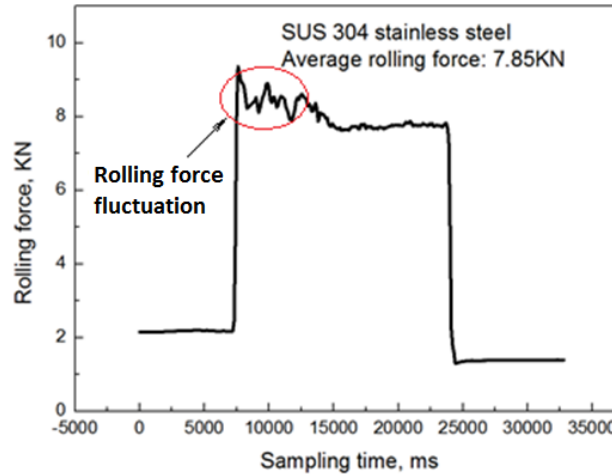


Fig. 11 Measured rolling force changes with sampling time in first pass, foil thickness: 100 μm

Fig. 11 shows the fluctuation of the measured rolling force with sampling time. Two pressure sensors are installed under both ends of the roll neck. The sensors are connected with the strain amplifier where so the rolling force can be recorded by the data logger as shown in Fig. 1. It can be seen that the rolling force variation is great when biting the rolling specimen in the rolling entrance as shown in the marked area in Fig. 11. After that, the rolling force reaches a steady state value with rolling process.

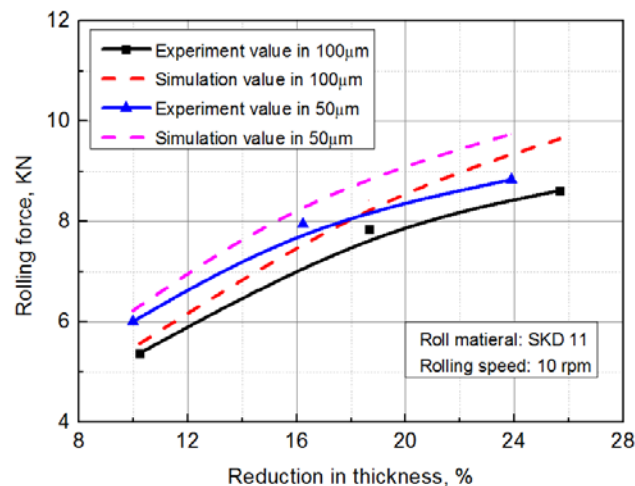


Fig. 12 Average rolling force versus rolling reduction

The rolling force comparison between the experiment and simulation is shown in Fig. 12. It can be seen that rolling force increases with increasing reduction in thickness. Through the comparison, the measured rolling forces are in agreement with the simulation results roughly and both graphs share the same upward sloping trend. The results of the experiment validate the simulation process. For the same reduction, the rolling force is higher in thinner foil than that in thicker foil.

In order to investigate the effect of elastic deformation of rolls on the foil deformation, two roll materials with different Young's Moduli are used in this simulation: SKD 11 and cemented carbide. Fig. 13 shows the effect of roll Young Modulus on the rolling force. It can be seen that more rolling force is required to obtain the

same reduction in thickness for SKD 11 than that for cemented carbide. The higher the Young's modulus of the roll material, the lower is roll flattening. Therefore it is possible to obtain more reduction in thickness for the rolled strip using cemented carbide as roll material.

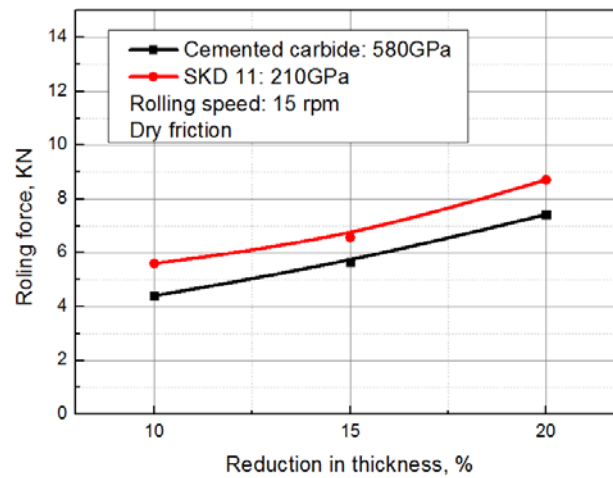


Fig. 13 Rolling force versus roll materials: SKD 11 and Cemented carbide

CONCLUSIONS

A 2-Hi micro rolling mill has been successfully set up in foil rolling process for SUS 304 stainless steel and high quality ultra-thin foil has been obtained. Experiment and FE simulation have comprehensively investigated on this kind of foil in micro rolling. The results show that the friction coefficient increases with increasing miniaturization and with sliding distance as well. The flow stress in microforming process is decreased with the scaling down of specimen size. The size effects are demonstrated by the stress strain curve and the friction coefficient. Surface roughness decreases with increasing pass reduction. The fact that simulation results of surface roughness and rolling force are in good agreement with the experimental values testifies the validation of proposed modelling. The research results are able to provide a basis for understanding of deformation behaviour and friction phenomenon in micro rolling.

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